INCREASING AN ELECTRICAL RESISTANCE OF A RESISTOR BY OXIDATION OR NITRIDIZATION

Background of the Invention

1. Technical Field

The present invention provides a method and structure for increasing an electrical resistance of a resistor that is located within a semiconductor structure such as a semiconductor wafer, a semiconductor chip, and an integrated circuit.

2. Related Art

A resistor on a wafer may have its electrical resistance trimmed by using laser ablation to remove a portion of the resistor. For example, the laser ablation may cut slots in the resistor. With existing technology, however, trimming a resistor by using laser ablation requires the resistor to have dimensions on the order of tens of microns. A method and structure is needed to increase the electrical resistance of a resistor on a wafer generally, and to increase the electrical resistance of a resistor having dimensions at a micron or sub-micron level.

Summary of the Invention

The present invention provides a method for increasing an electrical resistance of a resistor, comprising the steps of:

providing a semiconductor structure that includes the resistor; and

oxidizing a fraction F of a surface layer of the resistor with oxygen particles, resulting in the increasing of the electrical resistance of the resistor.

The present invention provides an electrical structure, comprising:

a semiconductor structure that includes a resistor; and

oxygen particles in an oxidizing reaction with a fraction F of a surface layer of the resistor, wherein the oxidizing reaction increases an electrical resistance of the resistor.

The present invention provides a method for increasing an electrical resistance of a resistor, comprising the steps of:

providing a semiconductor structure that includes the resistor; and

nitridizing a fraction F of a surface layer of the resistor with nitrogen particles, resulting in the increasing of the electrical resistance of the resistor.

The present invention provides an electrical structure, comprising:

a semiconductor structure that includes a resistor; and

nitrogen particles in an nitridizing reaction with a fraction F of a surface layer of the resistor, wherein the nitridizing reaction increases an electrical resistance of the resistor.

The present invention provides a method and structure for increasing an electrical resistance of a resistor on a wafer generally, and for increasing the electrical resistance of a resistor having dimensions at a micron or sub-micron level.

Brief Description of the Drawings

FIG. 1 depicts a front cross-sectional view of a semiconductor structure that includes an electrical resistor, in accordance with embodiments of the present invention.

FIG. 2 depicts FIG. 1 at an onset of exposure of a portion of the resistor to oxygen particles.

FIG. 3 depicts FIG. 2 after exposure of the portion of the resistor to the oxygen particles.

FIG. 4 depicts a front cross-sectional view of a heating chamber that includes the semiconductor structure of FIG. 2 and an oxygen-comprising gas, wherein the heating chamber generates heat that heats the semiconductor structure, in accordance with embodiments of the present invention.

FIG. 5 depicts a front cross-sectional view of a chamber that includes the semiconductor structure of FIG. 2 and an oxygen-comprising gas, wherein the resistor of the semiconductor structure is heated by a directed beam of radiation or particles, in accordance with embodiments of the present invention.

FIG. 6 depicts a front cross-sectional view of a plasma chamber that includes the semiconductor structure of FIG. 2, in accordance with embodiments of the present invention.

FIG. 7 depicts a front cross-sectional view of an anodization bath in which the semiconductor structure of FIG. 2 is partially immersed, in accordance with embodiments of the present invention.

FIG. 8 depicts a front cross-sectional view of a chemical bath in which the resistor of the semiconductor structure of FIG. 2 is immersed, in accordance with embodiments of the present invention.

FIG. 9 depicts FIG. 2 during exposure of the portion of the resistor to the oxygen particles, and with the resistor coupled to an electrical resistance measuring apparatus, in accordance with embodiments of the present invention.

Detailed Description of the Invention

FIG. 1 illustrates a front cross-sectional view of a semiconductor structure **10** that includes an electrical resistor **14** within a semiconductor substrate **12**, in accordance with

embodiments of the present invention. The electrical resistor **14** includes an electrically resistive material. The semiconductor structure **10** may include, *inter alia*, a semiconductor wafer, a semiconductor chip, an integrated circuit, etc. The substrate **12** comprises all portions of the semiconductor structure **10** (e.g., electronic devices including semiconductor devices, wiring levels, etc.) exclusive of the resistor **14**. The resistor **14** may have any electrical resistance functionality within the semiconductor substrate **12** and accordingly may exist within a semiconductor device, within an electrical circuit, etc. The resistor **14** includes an exposed surface **19** having a surface area S.

FIG. 2 illustrates FIG. 1 at an onset of exposure of a portion **15** of the resistor **14** to oxygen particles **20**. The oxygen particles **20** may comprise oxygen-comprising molecules (e.g., molecular oxygen O_2, carbon dioxide CO_2, etc.) or oxygen ions, depending on which of several embodiments of the present invention is operative, as will be discussed *infra*. The oxygen-exposed portion **15** has an oxygen-exposed surface **17** (i.e.; the surface **17** is exposed to the oxygen particles **20**). The resistor **14** includes an oxygen-unexposed portion **16** that has an oxygen-unexposed surface **18** (i.e.; the surface **18** is unexposed to the oxygen particles **20**). The surface **19** (see FIG. 1) comprises the surfaces **17** and **18** which have surface areas S_E and S_U, respectively. Thus the surface area S of the surface **19** (see FIG. 1) is $S_E + S_U$. In FIG. 2, the oxygen-unexposed portion **16** and the associated surface **18**, if present, gives rise to a "partially exposed" embodiment, since the surface **19** will be partially exposed to the oxygen particles **20** (at the surface **17**) such that $S_U > 0$. The oxygen-unexposed portion **16** and the associated surface **18**, if not present, gives rise to a "totally exposed" embodiment, since the surface **19** will be totally exposed to the oxygen particles **20** (at the surface **17**) such that $S_U = 0$.

FIG. 3 illustrates FIG. 2 after the exposure of the portion **15** of the resistor **14** to the

oxygen particles **20**. The exposure of the portion **15** of the resistor **14** for a finite time of exposure generates an oxidized region **22** within the portion **15**, wherein an unoxidized portion **24** of the resistor **14** remains. The oxidized region **22** is a fraction F of a surface layer of the resistor **14**, wherein the surface layer is a region defined as the oxidized region **22** projected to the side surfaces **25** and **26** of the resistor **14**. The fraction F is in a range of $0 < F \leq 1$, wherein $0 < F < 1$ corresponds to the "partially exposed" embodiment, and $F = 1$ corresponds to the "totally exposed" embodiment, discussed *supra*. The oxidized region **22** has a thickness t that may increase as the time of exposure increases or may reach a self-limiting thickness. For oxidation processes which are diffusion dominated, the thickness t may vary, *inter alia,* as a square root of the time of exposure. The oxidized region **22** increases an electrical resistance of the resistor **14** associated with current flow either in a direction **6** or in a direction **7**, in comparison with an electrical resistance of the resistor **14** that existed before the oxidized region **22** was formed.

The resistor **14** could be within an integrated circuit and, accordingly, FIG. 3 also shows in of the integrated circuit above the resistor **14**. The insulative layer **11** includes an insulative material **13** and an opening **23**, wherein the opening **23** which defines the resistor **14** that is potentially oxidizable in accordance with the present invention. Note that there may be resistive regions **28** underneath the insulative material **13** and thus blocked by the insulative material **13**. Accordingly, the underneath or blocked resistive regions **28** are not oxidizable in accordance with the present invention. Although not explicated or discussed in the embodiments described *infra*, the resistor **14** could be thought of as being "partially exposed" if the total resistor is defined as the resistor **14** in combination with the underneath or blocked resistive regions **28**.

The present invention includes five embodiments for oxidizing the resistor **14** to increase the electrical resistance of the resistor **14**, namely: thermal oxidation using a heating chamber

(FIG. 4); thermal oxidation using a direct beam of radiation or particles (FIG. 5); plasma oxidation (FIG. 6); anodization (FIG. 7); and chemical oxidation (FIG. 8). The following discussion will describe these embodiments and explain how *in situ* testing can be used to control the electrical resistance acquired by the resistor **14** after being exposed to the oxygen particles **20** (FIG. 9).

While the five embodiments mentioned *supra* and discussed *infra* specifically describe oxidizing the resistor **14**, the five embodiments mentioned *supra* and discussed *infra* are each applicable to changing an the resistance of the resistor **14** by nitridizing as an alternative to oxidizing. Nitridizing the resistor **14**, as opposed to oxidizing the resistor **14**, means reacting the resistor **14** with nitrogen particles (instead of with the oxygen particles **20**) in a manner that forms a nitride of the electrically resistive material of the resistor **14** comprises (instead of forming an oxide of electrically resistive material that the resistor **14**). As with the oxygen particles **20**, the nitrogen particles may be in molecular or ionic form depending on the operative embodiment. "Partially exposed" and "fully exposed" embodiments are applicable to nitridization of the resistor **14**, just as "partially exposed" and "fully exposed" embodiments are applicable to oxidation of the resistor **14**. Unless noted otherwise herein, all features and aspects of the five embodiments, as discussed *infra*, apply to nitridization of the resistor **14** just as said all features and aspects of the five embodiments apply to oxidation.

<u>Thermal Oxidation Using a Heating Chamber</u>

FIG. 4 illustrates a front cross-sectional view of a heating chamber **30** that includes an oxygen-comprising gas **32** and the semiconductor structure **10** of FIG. 2, in accordance with embodiments of the present invention. The gas **32** includes an oxygen compound such as, *inter*

alia, molecular oxygen (O_2), nitrous oxide (N_2O), carbon dioxide (CO_2), and carbon monoxide (CO).

The heating chamber **30** is heated to a heating temperature and the resistor **14** is thus oxidized by the gas **32** to form an oxide region within the resistor **14** such as the oxide region **22** depicted *supra* in FIG. 3. A thickness of the oxidized region (see, e.g., the thickness t of the oxidized region **22** described *supra* for FIG. 3) increases as a time of exposure of the resistor **14** to the gas **32** increases. FIG. 4 exemplifies a "totally exposed" embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) of the resistor **14** does not exist (i.e., $S_U = 0$ and $F = 1$), and the surface **17** is the total surface **19** (see FIG. 1) that is oxidized. In FIG. 4, the oxygen concentration in the ambient gas **32** and the heating temperature, in combination, should be sufficient to oxidize the resistor **14**. Said combinations depend on the chemistry of the oxidizing reaction between the resistor **14** and the gas **32**. Thus, the required oxygen concentration and heating temperature depends on a material composition of the resistor **14** and the gas **32**.

The gas **32** may be non-flowing in the form of a volumetric distribution within the heating chamber **30**. Alternatively, the gas **32** may be in a flowing form at low flow, wherein the gas **32** contacts the resistor **14**. Since the flowing gas **32** originates from a source that is likely to be substantially cooler than the heating temperature, the oxygen flow rate should be sufficiently slow as to minimize or substantially eliminate heat transfer from the resistor **14** to the gas **32**. Such inhibition of heat transfer may by any method known to one of ordinary skill in the art. One such method is for the oxygen flow to be slow enough that the dominant mode of said heat transfer is by natural convection rather than by forced convection. An additional alternative using flowing oxygen includes preheating the gas **32** to a temperature sufficiently close to the heating temperature so that said heat transfer is negligible even if said heat transfer occurs by

forced convection.

The heating chamber 30 in Fig. 4 includes any volumetric enclosure capable of heating the semiconductor structure **10** placed therein. The heat within the heating chamber **30** may be directed toward the semiconductor structure **10** in the direction **37** from a heat source **34** above the semiconductor structure **10**. The heat within the heating chamber **30** may also be directed toward the semiconductor structure **10** in the direction **38** from a heat source **36** below the semiconductor structure **10**. Heat directed from the heat source **34** in the direction **37** is transferred to the surface **17** more directly than is heat directed from the heat source **36** in the direction **38**. Accordingly, the heat directed from the heat source **34** in the direction **37** is more efficient for raising the temperature at the surface **17** than is the heat directed from the heat source **36** in the direction **38**. Either or both of the heat sources **34** and **36** may be utilized in the heating chamber **30**. Either or both of the heat sources **34** and **36** may be a continuous heat source or a distributed array of discrete heat sources such as a distributed array of incandescent bulbs. Alternatively, the heating chamber **30** may be a furnace.

Any method of achieving the aforementioned heating temperature in the heating chamber **30** is within the scope of the present invention. For example, the semiconductor structure **10** could be inserted into the heating chamber **30** when the heating chamber **30** is at ambient room temperature, followed by a rapid ramping up of temperature within the heating chamber **30** until the desired heating temperature is achieved therein. If the heating temperature is spatially uniform at and near the resistor **14**, then the oxidation of the resistor **14** in the direction **37** will be spatially uniform such that a thickness of the resultant oxide layer is about constant (see, e.g., the thickness t of the oxide layer **22** in FIG. 3 which is about constant). A spatially nonuniform heating temperature which would result in a oxide layer thickness that is not constant. Both

uniform and nonuniform heating temperature distributions, and consequent uniform and nonuniform oxide layer thicknesses, are within the scope of the present invention.

Suitable resistor **14** electrically resistive materials for being oxidized in the heating chamber **30** include, *inter alia*, one or more of polysilicon, amorphous silicon, titanium, tantalum, tungsten, aluminum, silver, copper, or nitrides, silicides, or alloys thereof.

The aforementioned method of oxidizing the resistor **14** using the heating chamber **30** does not depend on the dimensions of the resistor **14** and is thus applicable if the resistor **14** has dimensions of 1 micron or less, and is likewise applicable if the resistor **14** has dimensions in excess of 1 micron.

As stated *supra*, thermal nitridization using a heating chamber could be used as an alternative to thermal oxidation using a heating chamber. If nitridization is employed, the gas **32** would include, instead of an oxygen compound, a nitrogen compound such as, *inter alia*, molecular nitrogen (N_2).

Thermal Oxidation Using a Directed Beam of Radiation or Particles

FIG. 5 illustrates a front cross-sectional view of a chamber **40** that includes the semiconductor structure **10** of FIG. 2 and an oxygen-comprising gas **42**, wherein the resistor **14** of the semiconductor structure **10** is heated by a directed beam **46** of radiation or particles, in accordance with embodiments of the present invention. The gas **42** includes an oxygen compound such as, *inter alia*, molecular oxygen (O_2), nitrous oxide (N_2O), carbon dioxide (CO_2), and carbon monoxide (CO). The gas **42** may be non-flowing or flowing as discussed *supra* in conjunction with the gas **32** of FIG. 4

The portion **15** of the resistor **14** is heated to a heating temperature by the directed beam

46, and the portion **15** is thus oxidized by the gas **32** to form an oxide region within the resistor **14** such as the oxide region **22** depicted *supra* in FIG. 3. A thickness of the oxidized region (see, e.g., the thickness t of the oxidized region **22** described *supra* for FIG. 3) increases as a time of exposure of the resistor **14** to the directed beam **46** increases. The thickness of the oxidized region also increases as an energy flux of the directed beam **46** increases. The directed beam **46** may include radiation (e.g., laser radiation), or alternatively, a beam of particles (e.g., electrons, protons, ions, etc.). The directed beam **46** must be sufficiently energetic to provide the required heating of the resistor **14**, and a minimum required energy flux of the directed beam **46** depends on a material composition of the resistor **14**. Additionally, the directed beam **46** should be sufficiently focused so that the aforementioned energy flux requirement is satisfied.

If the directed beam **46** includes laser radiation, then the laser radiation may comprise a continuous laser radiation or a pulsed laser radiation. If the resistor **14** comprises a metal, then the present invention will be effective for a wide range of wavelengths of the laser radiation, since a metal is characterized by a continuum of energy levels of the conduction electrons rather than discrete energy levels for absorbing the laser radiation.

The directed beam **46**, which is generated by a source **44**, may be directed to the oxygen-exposed portion **15** of the resistor **14** in a manner that the oxygen-unexposed portion **16** of the resistor **14** exists. For example, the source **44** may include a laser whose spot size area is less than the surface area S of the total surface **19** (see FIG. 1) of the resistor **14**, and the associated directed beam **46** includes radiation from the laser of the source **44**. Thus it is possible for the laser beam to traverse less than the total surface **19**. Similarly, the source **44** may generate the directed beam **46** as the beam of particles, which impart energy to the resistor **14** and thus heat the resistor **14**. The directed beam **46** may be localized to the surface **17** which requires that the

directed beam **46** be sufficiently anisotropic; i.e., sufficiently localized to the direction **37** by the source **44**, which depends on physical and operational characteristics of the source **44**. Accordingly, if the directed beam **46** is localized to the surface **17**, then FIG. 5 would exemplify a "partially exposed" embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) exists (i.e., $S_U > 0$ and $F < 1$). Alternatively, FIG. 5 may also exemplify a "totally exposed" embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) does not exist (i.e., $S_U = 0$ and $F = 1$), since the directed beam **46** could be directed to the total surface **19**. Thus, FIG, 4 exemplifies either a "totally exposed" ($F = 1$) or a "partially exposed" ($F < 1$) embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) may or may not exist. A spatial extent of partial or total exposure to, and associated reaction with, the oxygen-comprising gas **42** may be controlled by adjusting the size (i.e., area) of the directed beam **46** and/or by scanning the directed beam **46** across portions of the total surface **19** (see FIG. 1).

In FIG. 5, the oxygen concentration in the gas **32** and the heating temperature, in combination, should be sufficient to oxidize the resistor **14**, and depends on the chemistry of the oxidizing reaction between the resistor **14** and the gas **32** as discussed *supra* in conjunction with FIG. 4. An ability to achieve the required temperature depends on the directed beam **46** being sufficiently energetic so as to impart enough energy to the portion **15** of the resistor **14** to facilitate the heating and consequent oxidation of the portion **15.** The energy of the directed beam **46** is controlled at its source **44**.

As stated *supra*, an advantage of using the directed beam **46** of FIG. 5 instead of the heating chamber **30** of FIG. 4 to heat the resistor **14** is the ability to heat less than the total exposed surface area **19** of the resistor **14**. Another advantage is that said heating of the semiconductor structure **10** by the heating chamber **30** could potentially damage thermally-

sensitive portions of the semiconductor structure **10** which cannot tolerate the temperature elevation caused by the heating chamber **30**. In contrast, the localized heating by the directed beam **46** advantageously does not expose said thermally-sensitive portions of the semiconductor structure **10** to potential thermally-induced damage.

Suitable resistor **14** electrically resistive materials for being oxidized while being heated by the directed beam **46** include, *inter alia*, one or more of polysilicon, amorphous silicon, titanium, tantalum, tungsten, aluminum, silver, copper, or nitrides, silicides, or alloys thereof.

If the directed beam **46** is required to be confined to the surface **19** (see FIG. 1) of the resistor **14** (i.e., if the directed beam **46** should not strike any surface of the resistor **14** other than the surface **19**), then dimensions of the surface **19** should be no smaller than a smallest surface area on which the directed beam **46** could be focused. For example, if the directed beam **46** includes laser radiation and the source **44** includes a laser, then the dimensions of the portion **15** of the resistor **14** may be no smaller than a laser spot dimension. Since with current and future projected technology, laser spot dimensions of the order of 1 micron or less are possible, the portion **15** of the resistor **14** may have dimensions of 1 micron or less (to an extent possible with prevailing laser technology at a time when the present invention is practiced), as well as dimensions exceeding 1 micron, when the directed beam **46** includes the laser radiation.

As stated *supra*, thermal nitridization using a directed beam of radiation or particles could be used as an alternative to thermal oxidation using a directed beam of radiation or particles. If nitridization is employed, the gas **42** would include, instead of an oxygen compound, a nitrogen compound such as, *inter alia*, molecular nitrogen (N_2).

Plasma Oxidation

FIG. 6 illustrates a front cross-sectional view of a plasma chamber **50** that comprises the semiconductor structure **10** of FIG. 2, in accordance with embodiments of the present invention. The plasma chamber **50** includes an electrode **54** and an electrode **55**. The semiconductor structure **10** has been disposed between the electrode **54** and the electrode **55**. The plasma chamber **50** also includes oxygen ions **52** which are formed in generation of a plasma gas, as will be explained *infra*.

A neutral gas within the plasma chamber **50** includes an oxygen compound such as, *inter alia*, molecular oxygen (O_2), nitrous oxide (N_2O), carbon dioxide (CO_2), and carbon monoxide (CO). Inasmuch as a plasma gas will be formed from the neutral gas, the plasma chamber **50** may also include one or more noble gases (e.g., argon, helium, nitrogen, etc.) to perform such functions as: acting as a carrier gas, providing electric charge needed for forming ionic species of the plasma, assisting in confining the plasma to within fixed boundaries, assisting in developing a target plasma density or a target plasma density range, and promoting excited state plasma lifetimes.

A power supply **56** generates an electrical potential between the electrode **54** and the electrode **55**. The power supply **56** may be of any type known to one skilled in the art such as, *inter alia*: a radio frequency (RF) power supply; a constant voltage pulsed power supply (see, e.g., U.S. Patent 5, 917, 286, June 1999, Scholl et al.); and a direct current (DC) voltage source (see, e.g., U.S. Patent 4,292,384, September 1981, Straughan et al.). Pertinent characteristics of the power supply **56** are in accordance with such characteristics as are known in the art. For example, a RF power supply may include, *inter alia*, a radio frequency selected from a wide range of frequencies such as a commonly used frequency of 13.56 Hz. The power requirements

of the RF power supply depends on the surface area **17** of the resistor **14** and is thus case dependent. For example, a typical range of power of the RF power supply may be, *inter alia*, between about 100 watts and about 2000 watts.

The electrical potential generated by the power supply **56** ionizes the neutral gas to form a plasma between the electrode **54** and the electrode **55**, wherein the plasma comprises electrons and ions, and wherein a plasma ion polarity depends on the particular neutral gas within the plasma chamber **50**. For example, if the neutral gas includes molecular oxygen, then a three-component plasma may be formed including electrons, positive oxygen ions, and negative oxygen ions, such that in the glow discharge a predominant positive ion is O_2^+ and a lesser positive ionic species is O^+. See U.S. Patent 5,005,101 (Gallagher et al.; April 1991; col. 6, lines 1-12).

In FIG. 6, a DC power supply **57** has terminals **58** and **59**, wherein the terminal **58** is positive with respect to a ground **51**, and the terminal **59** is negative with respect to the terminal **58**. The DC power supply **57** generates an electric field that is directed from the electrode **54** to the electrode **55**, and the electric field is capable of accelerating positive ions from the electrode **54** toward the electrode **55** in the direction **37**. Accordingly, if the oxygen ions **52** are positive oxygen ions (e.g., O_2^+) , then the electric field accelerates the oxygen ions **52** of the plasma toward the electrode **55** causing the oxygen ions **52** to strike the portion **15** of the resistor. If the oxygen ions **52** are sufficiently energetic (i.e., if the oxygen ions **52** have a minimum or threshold energy) as required to oxidize the portion **15** of the resistor **14**, then the oxygen ions **52** will so oxidize the portion **15** and thus form an oxidized region within the resistor **14**, such as the oxidized region **22** depicted *supra* in FIG. 3. A thickness of the oxidized region (see, e.g., the thickness t of the oxidized region **22** described *supra* for FIG. 3) increases as a time of exposure

of the resistor **14** to the accelerated oxygen ionic species **52** increases.

If the oxygen ions **52** are negative oxygen ions to be accelerated toward the resistor **14** and reacted with the resistor **14**, then the polarities of the terminals **58** and **59** should be reversed (i.e., the terminals **58** and **59** should have negative and positive polarities, respectively). A factor in determining whether positive or negative oxygen ions **52** are to be reacted with the resistor **14** includes consideration of the chemical reactions between said accelerated oxygen ions **52** and the electrically resistive material of the resistor **14**, since characteristics of said chemical reactions (e.g., reaction energetics, reaction rate, etc.) may be a function of the polarity of the reacting ionic oxygen species **52**. Nonetheless, if negative oxygen ions **52** of the plasma are accelerated by the DC power supply **57** toward the resistor **14**, then electrons of the plasma will also be accelerated toward the resistor **14**, which in some situations may result in undesirable interactions between said electrons and the resistor **14**. Thus, each of the aforementioned considerations (e.g., material of the resistor **14**, characteristics of the chemical reactions between the oxygen ions **52** and the resistor **14**, etc.) must be considered when choosing the neutral gas and choosing which ionic species **52** to react with the resistor **14**.

The accelerated oxygen ions **52** transfer energy to the resistor **14** to provide at least the threshold energy required for effectuating the chemical reaction between the oxygen ions **52** and the resistor **14**, and such energy transferred substitutes for thermal energy (i.e., heat) provided by the heating chamber **30** of FIG. 4, or by the directed beam **46** of radiation or particles of FIG. 5, to the resistor **14**. A voltage output of the DC power supply **57** must be sufficient to accelerate the oxygen ions **52** to at least the aforementioned threshold energy.

FIG. 6 exemplifies a "totally exposed" embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) of the resistor **14** does not exist (i.e., $S_U = 0$ and $F = 1$), and the surface **17**

is the total surface **19** (see FIG. 1) that is oxidized in the plasma chamber **50**.

While FIG. 6 depicts a particular plasma chamber **50** configuration for oxidizing the resistor **14**, any plasma configuration known to one of ordinary skill in the art may be used.

Suitable resistor **14** electrically resistive materials for being subject to plasma oxidation include, *inter alia*, one or more of polysilicon, amorphous silicon, titanium, tantalum, tungsten, aluminum, silver, copper, or nitrides, silicides, or alloys thereof.

The aforementioned method of oxidizing the resistor **14** using plasma oxidation does not depend on the dimensions of the resistor **14** and is thus applicable if the resistor **14** has dimensions of 1 micron or less, and is likewise applicable if the resistor **14** has dimensions in excess of 1 micron.

As stated *supra*, plasma nitridization using a directed beam of radiation or particles could be used as an alternative to plasma oxidation using a directed beam of radiation or particles. If nitridization is employed, the neutral gas within the plasma chamber **50** would include, instead of an oxygen compound, a nitrogen compound such as, *inter alia*, molecular nitrogen (N_2).

<u>Anodization</u>

FIG. 7 illustrates a front cross-sectional view of an anodization bath **60**, in accordance with embodiments of the present invention. Generally, anodizing a first conductive material such as a semiconductor or metal requires immersing into an electrolytic solution both the first conductive material and a second conductive material, and passing a DC current at a sufficient voltage through the electrolytic solution.

An anodization electrical circuit **69** includes a DC power supply **64**, an electrolytic solution **61** which includes oxygen, the semiconductor structure **10** of FIG. 2 wherein the resistor

14 is partially immersed in the electrolytic solution 61, and an electrode 63 partially immersed in the electrolytic solution 61. "Partially immersed" includes "totally immersed" (i.e., 100% immersed) as a special case. The resistor 14 is made of the electrically resistive material which includes the first conductive material that serves as an anode, and the electrode 63 is made of the second conductive material that serves as a cathode. The second conductive material of the cathode may include any inert metal (e.g., platinum) that does not react with the electrolytic solution 61. The resistor 14 is made anodic by electrically coupling the resistor 14 to a positive terminal 65 of the DC power supply 64. The electrode 63 is made cathodic by electrically coupling the electrode 63 to a negative terminal 66 of the DC power supply 64. The anodization may be performed at or above ambient room temperature. A thickness of an oxide film formed with the resistor 14 is a function of a voltage output from the DC power supply 64 and the current density in the anodization circuit 69. The specific voltage and current density is application dependent and would be selected from known art by one of ordinary skill in the art. For example, an anodization of tantalum or tantalum nitride at ambient room temperature and at with a current density of about 0.1 milliamp/cm^2 in an electrolytic solution of citric acid will generate an oxide (i.e., tantalum pentoxide Ta_2O_5) film thickness of 20 Å per volt. Thus for an applied voltage of about 25 volts, the Ta_2O_5 film thickness is about 500 Å..

Suitable resistor 14 electrically resistive materials for being anodized include, *inter alia*, . Suitable cathode 63 materials include, *inter alia* tantalum, titanium, polysilicon, aluminum, tungsten, nitrides thereof, and alloys thereof. A electrolyte containing oxygen that can be used depends on the electrically resistive material to be anodized and is therefore case specific. Thus, any electrolyte containing oxygen that is compatible with said electrically resistive material may be selected as would be known or apparent to one of ordinary skill in the art.

Upon activation of the DC power supply **64** (i.e., the DC power supply **64** is turned on), and under the voltage output (and the associated current) from the DC power supply **64**, an electrolytic reaction occurs at the surface **17** of the resistor **14** to generate hydrogen ions, electrons, and oxygen ions **62** from the electrolytic solution. The oxygen ions **62** chemically react with the portion **15** of the resistor **14** such that an oxidized region, such as the oxidized region **22** depicted *supra* in FIG. 3, forms within the portion **15** of the resistor **14**. The generated hydrogen ions and electrons combine at the cathode **63** to form hydrogen gas.

FIG. 7 shows the portion **16** of the resistor **14** above an electrolyte level **67**. Accordingly, FIG. 7 may exemplify a "partially exposed" embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) exists (i.e., $S_U > 0$ and $F < 1$). Alternatively, FIG. 7 may also exemplify a "totally exposed" embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) does not exist (i.e., $S_U = 0$ and $F = 1$) if the resistor **14** is totally immersed in the electrolytic solution **61**. Thus, FIG. 7 exemplifies either a "partially exposed" embodiment or a "totally exposed" embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) exists or does not exist, respectively.

A thickness of the oxidized region (see, e.g., the thickness t of the oxidized region **22** described *supra* for FIG. 3) increases as a time of the electrolytic reaction increases. As the thickness of the oxidized region increases, a current drawn by the anodizing bath **60** decreases due to increasing isolation of the portion **15** of the resistor **14** from the electrolytic solution **61** as the thickness of the oxidized layer increases. For certain resistor **14** materials (e.g., aluminum), the anodization process may eventually self terminate, because said current is eventually reduced to a negligible value.

The aforementioned method of oxidizing the resistor **14** using anodization does not

depend on the dimensions of the resistor **14** and is thus applicable if the portion **15** of the resistor **14** has dimensions of 1 micron or less, and is likewise applicable if the portion **15** of the resistor **14** has dimensions in excess of 1 micron.1

As stated *supra*, anodization that causes nitridization of the resistor **14** could be used as an alternative to anodization that causes oxidation of the resistor **14**. If anodization with nitridization is employed instead of anodization with oxidation, then the electrolytic solution **61** would include nitrogen instead of oxygen. An electrolyte containing nitrogen that can be used depends on the electrically resistive material to be anodized and is therefore case specific. Thus, any electrolyte containing nitrogen that is compatible with said electrically resistive material may be selected as would be known or apparent to one of ordinary skill in the art.

Chemical Oxidation

FIG. 8 illustrates a front cross-sectional view of a chemical bath **70**, in accordance with embodiments of the present invention. The chemical bath **70** comprises a chemical solution **71**. The semiconductor structure **10** of FIG. 2 is immersed in the chemical solution **71**. The chemical solution **71** includes oxygen particles **72** in such form as oxygen-comprising liquid molecules, oxygen ions, or an oxygen-comprising gas (e.g., oxygen gas or ozone gas) dissolved in the chemical solution **71** under pressurization. The oxygen particles **72** chemically react with the resistor **14** to form an oxidized region within the resistor **14** such as the oxidized region **22** depicted *supra* in FIG. 3. A thickness of the oxidized region (see, e.g., the thickness t of the oxidized region **22** described *supra* for FIG. 3) increases as a time of the chemical reaction increases. The chemical reaction may be exothermic or endothermic, depending on the electrically resistive material of the resistor **14** and the oxygen particles **72**. If the chemical

reaction is endothermic, an addition of a sufficient amount of heat is required. Additionally, a suitable catalyst may be utilized to accelerate the chemical reaction. The catalyst may be any catalyst known to one of ordinary skill in the art for the particular chemical reaction.

Suitable resistor **14** electrically resistive materials for being chemically oxidized include, *inter alia*, copper, tungsten, aluminum, titanium, nitrides thereof, and alloys thereof. Suitable chemical solutions **71** include, *inter alia*, hydrogen peroxide, ferric nitrate, ammonium persulphate, etc.

FIG. 8 shows the resistor **14** as totally immersed in the chemical solution **71**, which exemplifies a "totally exposed" embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) of the resistor **14** does not exist (i.e., $S_U = 0$ and $F = 1$), and the surface **17** is the total surface **19** (see FIG. 1) that is oxidized in the chemical solution **71**. Nonetheless, the resistor **14** could be rotated 90 degrees (within the cross-section plane illustrated in FIG. 8) and moved upward in a direction **75** such that a portion of the resistor **14** would be above the level **77** of the chemical solution **71** just as the portion **16** is above the electrolyte level **67** in FIG. 7. Under such 90 degree rotation and upward movement, FIG. 8 would represent a "partially exposed" embodiment in which the oxygen-unexposed portion **16** (See FIG. 2) exists (i.e., $S_U > 0$ and $F < 1$). Accordingly, FIG 8 exemplifies either a "partially exposed" embodiment or a "totally exposed" embodiment in which the oxygen-unexposed portion **16** (see FIG. 2) exists or does not exist, respectively.

The aforementioned method of oxidizing the resistor **14** using chemical oxidation does not depend on the dimensions of the resistor **14** and is thus applicable if the resistor **14** has dimensions of 1 micron or less, and is likewise applicable if the resistor **14** has dimensions in excess of 1 micron.

As stated *supra*, chemical nitridization of the resistor **14** could be used as an alternative to chemical oxidation of the resistor **14**. If chemical nitridization is employed instead of chemical oxidation, then the chemical solution **71** would include nitrogen particles instead of the oxygen particles **72**.

Resistance Testing

The resistor **14** may be tested prior to being oxidized or nitridized, while being oxidized or nitridized (i.e., *in situ*), and/or after being oxidized or nitridized. The resistance testing may be accomplished by a conventional test apparatus, such as with a four-point resistance test having four contacts to the resistor with two of the contacts coupled to a known current source outputting a current I and the other two contacts coupled to a voltage meter that measures a voltage V across the resistance to be determined, and the measured resistance is thus V/I. Alternatively, the resistance testing may be accomplished with an inline measuring circuit within the same integrated circuit that includes the resistor, wherein the measuring circuit is coupled to instrumentation that outputs the measured resistance.

FIG. 9 illustrates FIG. 2 during exposure of the portion **15** of the resistor **14** to the oxygen particles **20**, and with the resistor **14** coupled to an electrical resistance measuring apparatus **85**. The electrical resistance measuring apparatus **85** may include the conventional test apparatus or the inline measuring circuit, mentioned *supra*. The electrical resistance measuring apparatus **85** may be conductively coupled to surfaces **81** and **82** of the resistor **14** by conductive interconnects (e.g., conductive wiring) **86** and **87**, respectively. Accordingly, the electrical resistance measuring apparatus **85** is capable of measuring an electrical resistance of the resistor **14** (before, during, and after oxidation or nitridization of the resistor **14**) associated with current flowing in

the direction **7** through the resistor **14**. Alternatively, the electrical resistance measuring apparatus **85** may be used to measure an electrical resistance of the resistor **14** associated with current flowing in the direction **6** through the resistor **14** (before, during, and after oxidation or nitridization of the resistor **14**) if the conductive interconnects **86** and **87** are coupled to bounding surfaces **83** and **84** of the resistor **14** instead of to the surfaces **81** and **82**, respectively. The surface **83** in FIG. 9 corresponds to the surface **19** in FIG. 1. In FIG. 9, the resistor **14** includes an oxidized (or nitridized) region **21**, which corresponds to the oxidized (or nitridized) region **22** of FIG. 3. The semiconductor structure **10** is within an oxidizing (or nitridizing) environment **80**, which includes any oxidizing (or nitridizing) environment within the scope of the present invention such, *inter alia*, the heating chamber **30** of FIG. 4, the chamber **40** of FIG. 5, the plasma chamber **50** of FIG. 6, the anodization bath **60** of FIG. 7, and the chemical bath **70** of FIG. 8. The electrical resistance measuring apparatus **85** is any apparatus, as is known to one of ordinary skill in the art, capable of measuring an electrical resistance of the resistor **14**.

The following discussion describes how the electrical resistance measuring apparatus **85** of FIG. 9 can be used for *in situ* testing to control the electrical resistance acquired by the resistor **14** after being exposed to the oxygen particles **20**. The following discussion applies to any of the embodiments described *supra* (i.e., thermal oxidation or nitridization using a heating chamber, thermal oxidation or nitridization using a directed beam of radiation or particles, plasma oxidation/nitridization, anodization, and chemical oxidation/nitridization).

Let R_1 denote an electrical resistance of the resistor **14** prior to being oxidized or nitridized. Let R_2 denote a final electrical resistance of the resistor **14** (i.e., an electrical resistance of the resistor **14** after being oxidized or nitridized). Let R_t denote a predetermined target electrical resistance with an associated resistance tolerance ΔR_t for the resistor **14** after the

oxidation (or nitridization) has been completed (i.e., it is intended that $R_2 = R_t$ within the tolerance ΔR_t). The target electrical resistance R_t is application dependent. For example, in an analog circuit R_t may be a function of a capacitance in the circuit, wherein for the given capacitance, R_t has a value that constrains the width of a resonance peak to a predetermined upper limit. In practice, the predetermined resistance R_t, together with the associated resistance tolerance ΔR_t, may be provided for the intended application.

The resistor **14** may have its electrical resistance tested during or after the exposure of the resistor **14** to the oxygen particles **20**. As stated *supra*, the thickness t of the oxidized (or nitridized) region **22** (see FIG. 3) increases as the time of said exposure increases, and the electrical resistance of the resistor **14** increases as the thickness t increases. Thus, the final electrical resistance may be controlled by selection of the time of exposure. The time of exposure may be selected based on any method or criteria designed to obtain R_2 as being within $R_t \pm \Delta R_t$ (i.e., $R_t - \Delta R_t \leq R_2 \leq R_t + \Delta R_t$). For example, calibration curves derived from prior experience may be used for determining the time of exposure that results in R_2 being within $R_t \pm \Delta R_t$.

An iterative testing procedure may be utilized such that the electrical resistance of the resistor **14** is tested during the exposing of the resistor **14** to the oxygen particles **20** and thus during the oxidizing (or nitridizing) of the resistor **14**. The testing during the exposing of the resistor **14** to the oxygen particles **20** determines continuously or periodically whether R_2'' is within $R_t \pm \Delta R_t$, wherein R_2'' is the latest resistance of the resistor **14** as determined by the testing. The testing is terminated if R_2'' is within $R_t \pm \Delta R_t$ or if $(R_2''-R_1)(R_t-R_2'') \leq 0$.

While particular embodiments of the present invention have been described herein for purposes of illustration, many modifications and changes will become apparent to those skilled

in the art. Accordingly, the appended claims are intended to encompass all such modifications and changes as fall within the true spirit and scope of this invention.